

**Biological Evaluation of
Hemlock Woolly Adelgid
At
Wayne National Forest, Ohio, U.S.A.
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ABSTRACT

In January 2021, personnel from the USDA Forest Service, Northeastern Area, Forest Health Protection, Morgantown Field Office and Wayne National Forest conducted a survey to evaluate hemlock woolly adelgid (HWA), *Adelges tsugae*, to determine its presence and level of infestation within the Wayne National Forest. Three hemlock stands within the Marietta and Ironton Ranger Districts were inspected and HWA was found in two of the three stands (one in each ranger district). This was the first find of HWA on the Wayne NF. Both infestations, however, appear to have started recently and have yet to cause high levels of tree damage. Chemical treatment to control HWA on accessible, individual, high-value infested hemlock trees is recommended to prevent further decline of tree health. The release of predatory beetles, when available, is also recommended as a biological control strategy and future control of HWA.

INTRODUCTION

Hemlock Woolly Adelgid

Hemlock woolly adelgid (HWA, *Adelges tsugae*), an invasive insect in eastern North America, is believed to have been introduced from Japan sometime prior to 1951 (Havill and Foottit 2007). Due to its limited mobility, spread had been slow but by the late 1980s and 1990s HWA population had expanded and was reported to be causing widespread hemlock mortality (Cheah et al. 2004). HWA is currently established in 20 eastern states, with contiguous populations found from Georgia to Maine and a disjunct population in Michigan. In addition, it can also be found in Nova Scotia and Ontario, Canada (Figure 1, USDA 2021). Another population of HWA that is considered native can also be found in the Pacific Northwest region of North America where it is thought to have been introduced approximately 20,000 years ago (Havill et al. 2016). The western North American and Asian populations are not normally considered pests and only occasionally build to high enough numbers to impact ornamental trees (McClure 1987).

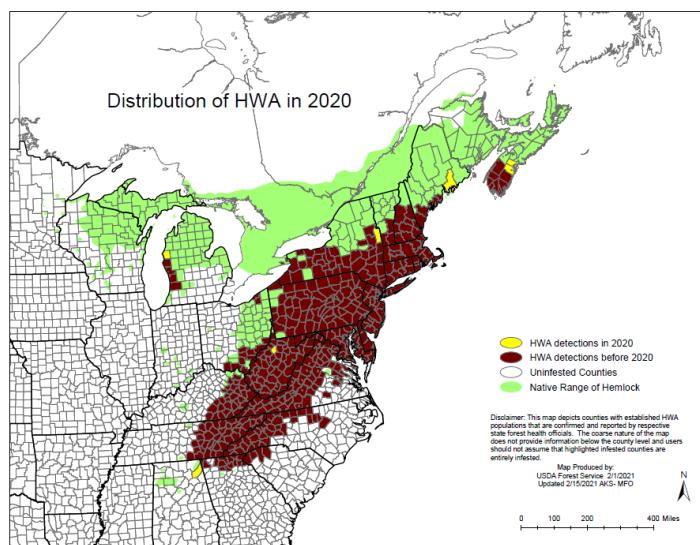


Figure 1. County level geographic range of HWA as of 2020.

Hemlock woolly adelgid is a pest of eastern hemlock (*Tsuga canadensis*) and Carolina hemlock (*T. caroliniana*) (Onken et al. 1999), both of which are considered highly susceptible to the adelgid

(Bentz et al. 2002). Despite this high susceptibility, a recent field study of hemlock from a stand in NJ that appeared to be resistant to HWA found a significant reduction in tree mortality in a paired study design with 95% survival in the “resistant” clones when compared to 48% of the non-resistant trees after four years (Kinahan et al. 2020). In Japan, HWA has two host species that includes tiger-tail spruce (*Picea torano* K. Koch), that serves as the primary host, and hemlock, that is the secondary host. On the primary host (spruce) HWA can produce a sexual generation. Because of the lack of primary host, a sexual generation is absent in North America.

In eastern North America, HWA has two wingless parthenogenic (females that produce females without the presence of males) generations and also produces a winged sexupara (female that seeks the primary host and can produce a sexual generation). Because there is no primary host for the sexupara to find and have a sexual generation, there are no males in the eastern North America population. Also, because HWA have parthenogenic reproduction, there is only the need for one individual to start a new infestation.

The Winter generation (sistens) develops from early summer and lives until midspring of the following year (June-March). A second Spring generation (progrediens) develops early Spring and completes its life cycle by early Summer (March-June) (Figure 2). The generations overlap in mid to late Spring. The winter generation takes longer to finish its life cycle due to a period of heat induced dormancy (aestivation) that takes place from July to late September/October.

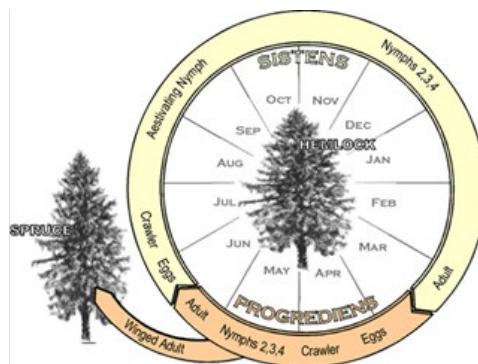


Figure 2. Life cycle of hemlock woolly adelgid on hemlock in North America (Ward et al. 2004)

Although HWA is sensitive to extreme cold temperatures and experiences mortality due to cold in the winter months, they are active in cooler periods of the year (through the Winter) and go into a dormancy period triggered by high summer temperatures (aestivation) that lasts from July through October (Limbu et al. 2018). This dormancy experienced by the Winter generation is the main reason for the different length of two generations life cycle; the Spring generation can be induced to go dormant if the same abiotic conditions exist (Weed et al. 2016). After egg hatch the first instar nymphs (crawlers) move to a spot on the twig at the base of a needle and inserts their stylet (mouth parts) and remains there for remainder of their life span. In the Winter generation prior to dormancy, the nymphs produce a halo of wool-like filament around their bodies. The dormancy period ends in Fall, typically in late September/early October.

Survival during summer dormancy is >80% when summer temperatures remain <25°C (77°F), but survival decreases as temperatures increase and with increased duration (Sussky and Elkington 2015, Mech et al. 2017). Exposure to direct sunlight can also contribute to reduced survival in dormant HWA (Brantley et al. 2017). After becoming active again in late Fall, the

Winter generation finish their life cycle by March. Winter cold can cause substantial mortality and this mortality can exceed 90% when temperatures fall below -20°C (-4°F) and can reach 100% at temperatures below -35 (-31°F) to -40°C (-40°F) (Parker et al. 1998, 1999, Butin et al. 2005, Paradis et al. 2008, Trotter and Shields 2009, Cheah 2017). Cold temperatures in the northern part of the range of hemlock in North America result in mortality of HWA, which helps slow the rate of hemlock mortality and determines the ability of HWA to establish in new areas with cold temperatures (Skinner et al. 2003, Trotter and Shields 2009). There is new evidence, however, that HWA in northeastern United States are showing signs of genetic adaptation to colder winter temperatures than those that occur in the southeastern United States (Skinner et al. 2003, Butin et al. 2005, Elkington et al. 2017, Lombardo and Elkington 2017).

As HWA mature, they produce a wooly covering that increases in size and becomes more conspicuous. This woolly sac (ovisac) helps protect the insect and its eggs from natural enemies and prevents them from drying out. The ovisacs can be readily observed from late fall to early summer on the underside of branch tips of hemlock trees and are used to determine the presence of HWA (Figure 4). Females of the winter generation lay up to 300 eggs, while the spring generation only lay 100 eggs per female (McClure et al. 2001).



Figure 3. Hemlock woolly adelgid nymphs with halo of filament in dormancy.



Figure 4. Hemlock woolly adelgid ovisacs on underside of branches.

Natural mortality in HWA populations is commonly between 30 to 60 percent (McClure 1989, 1996) but reproduction potential of this insect remains high due to its parthenogenetic reproduction. Mortality is generally attributed to two likely causes: 1) an extended period of cold temperatures or rapid temperature changes that coincides with a susceptible period of development for the adelgid, and 2) a sufficient loss in the nutritional quality and quantity of the food source associated with the decline in health and vigor of the host tree (McClure 1996, Onken et al. 1999).

Hemlock wooly adelgid feeding can kill mature hemlock and individual trees can be killed in about 5 to 7 years (McClure et al. 2001). They feed on all life stages of hemlock, from seedling to mature, old growth trees. Although tree mortality does not occur rapidly, HWA are known to kill entire stands and threaten to functionally extirpate hemlock in many areas.

HWA feed on storage cells within branch twigs. The first instar nymphs (crawlers) search for suitable sites at the base of the hemlock needles and insert their feeding stylets into the young

hemlock twigs and are committed to that feeding site throughout the remainder of its development. HWA does not deplete nutrients directly by feeding on the sap, but rather by depleting the food reserves from the tree's storage cells (McClure et al. 2001).

Although HWA spends most of its life in one place with its stylet attached to a fine branch, it has a good ability to disperse to new sites. The eggs and first instar nymphs are dispersed by wind, birds, animals, and humans (McClure 1990). Airborne HWA have been captured 600 m from an infestations and deer and birds tested near infested hemlock commonly had eggs and crawlers on them (McClure 1990). Their spread is estimated at about 15 km per year in the South and 8 km per year in the North (Evans and Gregoire 2007a). Human movement is thought to occur through the movement of nursery stock (McClure 1990) and it is believed that HWA was first introduced to North America through infested seedlings.

HEMLOCK IMPORTANCE

Eastern hemlock is a long-lived conifer that provides and supports a unique community of terrestrial and aquatic organisms for which there is no known tree species that can replace its ecological function (Ward et al. 2004). It is extremely shade tolerant and can survive up to 350 years underneath a shaded forest canopy (Quimby 1996). It takes 250-300 years to reach maturity and can live 800 years (Godman and Lancaster 1990). Eastern hemlock creates cool, moist microclimates with slow rates of nutrient cycling due to deep shade, which leads to slow decomposition of organic litter that is unique to hemlock-dominated forest (Ellison et al. 2010). They are also known for their ability to mediate soil moisture, stabilize stream base-flow, and regulate stream temperature (Barden 1979, Brantley et al. 2013). These distinctive microclimates provide important habitat for a variety of wildlife such as birds, fish, invertebrates, amphibians, reptiles and mammals; in the Northeast, 96 bird species and 47 mammal species are associated with hemlock at some point during their life (Yamasaki et al. 2000). For example, an avian study conducted in Delaware Water Gap National Recreation Area found that the Acadian flycatcher (*Empidonax virescens*), blue-headed vireo (*Vireo solitarius*), black-throated green warbler (*Dendroica virens*), and Blackburnian warbler (*Dendroica fusca*) showed a high affinity for hemlock forest type and exhibited significantly greater numbers of territories in hemlock than hardwood sites (Ross et al. 2004).

Hemlocks create a cooling effect in summer that is a critical factor in supporting trout populations and studies have shown that removal of hemlock trees within 80 feet of a stream can cause temperatures to rise 6 to 9 degrees Celsius (Lapin 1994). Aquatic macroinvertebrates were significantly higher in streams surround by hemlock when compared to hardwood forests and hemlock surrounded streams were less likely to dry up during dry summer periods (Snyder et al. 1998).

Hemlock stands are somewhat rare on the Wayne National Forest, with an estimated 190 acres mapped, mainly in small stands on the Marietta and Ironton Ranger Districts. With a limited number of acres and unique habitat characteristics, the hemlock on the Wayne should be considered for management activities that aim to retain these stands and the unique habitat they provide.

METHODS

Hemlock wooly adelgid was first found in a forest setting in Ohio in 2012 in Meigs County. Since then it has been slowly spreading across Ohio but had not been found specifically in stands within the Wayne NF as of 2020. Therefore, our first question was whether HWA was present on the Wayne and, if so, at what level of severity were any infested stands. Hemlock on the Wayne NF consists of small stringers (skinny stands that follow along small to medium sized drainages) scattered throughout the forest and covers approximately 190 acres; stands range from one to ten acres and can be found in the Marietta and Ironton Ranger Districts.

In January 2021, three hemlock stands were visited to survey for the presence and severity of HWA, one in the Marietta RD (Figure 5, New Matamoras) and two stands in the Ironton RD (Figure 6, Lake Vesuvius and Lick Branch). In addition, an additional nine sites in the Marietta RD were visited by forest technicians in a less formal survey to look for HWA.

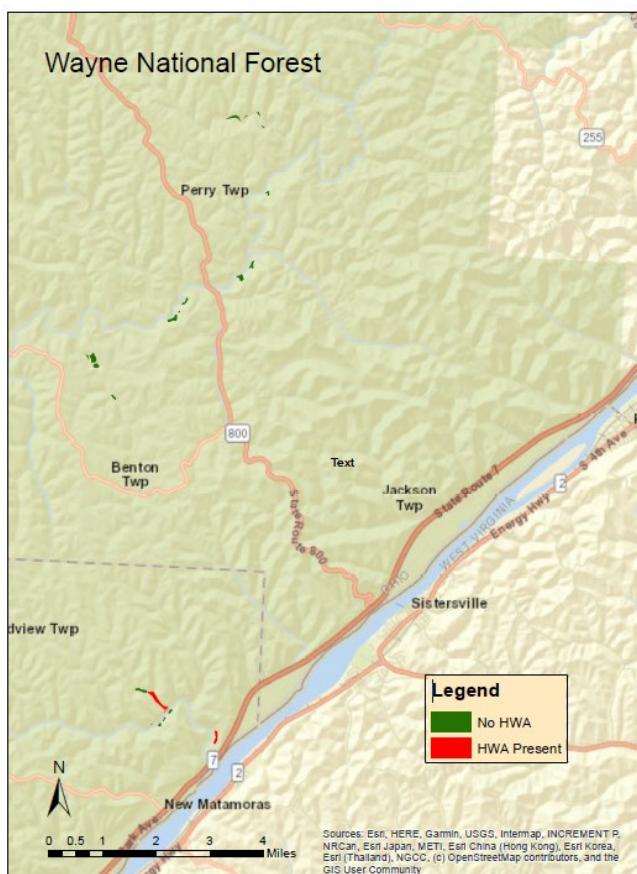


Figure 5. Hemlocks stands surveyed for the presence of HWA in Winter 2021 in Marietta RD, Wayne National Forest

100 trees where inspected.

The survey method we used for the evaluation of HWA populations was based on the sampling plan developed by Costa and Onken (2006). This sampling method is designed to determine the presence of HWA within a stand and estimate the percent of the stand infected. This method looks at two branches per tree on up to 100 trees scattered across the stand. Because of the clumpy distribution of HWA at low infestation levels, it is important that the hemlock observed are spread out throughout the stand to increase the probability of finding any infested trees. This method also allows for the observer to stop the survey after looking at just eight trees if most inspected trees are infested. Because our stands were small and we had enough technicians available, we decided that we would be able to easily look at a high proportion of each stand if we looked at 100 trees per stand. Following transects that followed the general shape of each stand we inspected two branches on the closest hemlock we encountered every one chain (66 ft) until

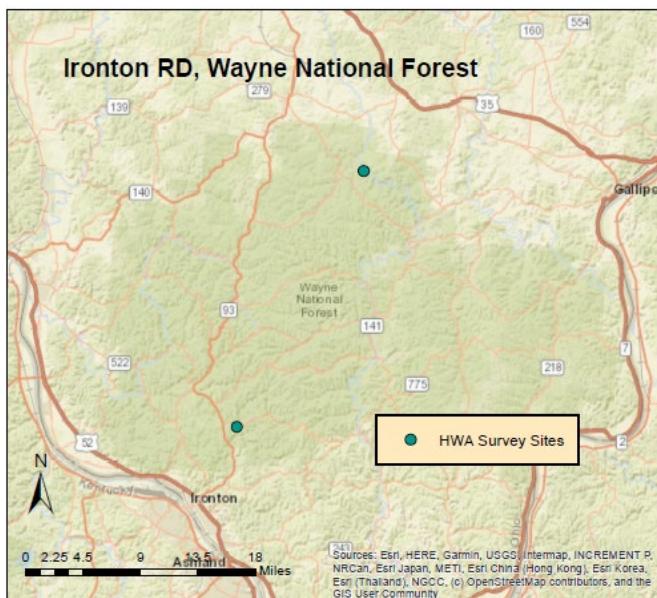


Figure 6. Locations of the stands inspected for HWA on the Ironton RD: Lick Branch is to the north and Lake Vesuvius to the south.

In addition to the stand level assessment, notes were taken on the general health of the hemlocks in the stand and the infestation level of an infested trees found (e.g., light or heavy infestation level).

RESULTS

HWA were found at two out of the three sites surveyed with our formal survey and at one of the additional stands in the Marietta RD surveys. At the three stands the hemlock were healthy with no visible needle loss due to HWA feeding. HWA were found on both the Marietta and Ironton Ranger Districts.



At the New Matamoras stand we found 16 hemlock with HWA out of 213 inspected (7.5%). All HWA positive trees had light infestation levels. On the Ironton RD, at the Lake Vesuvius stand we found 9 positive trees out of 18 inspected. Hemlock crowns in this stand were also healthy. At the Lick Branch site, we looked at 76 trees and didn't find any HWA.

DISCUSSION

During our Winter 2021 HWA field surveys we determined that HWA is present in hemlock stands in both the Marietta and Ironton Ranger Districts. The infestations we found were light and appeared to be relatively new, as trees had yet to show signs of crown damage. Although HWA presence is disconcerting, our results suggest that we have time to implement an HWA management program prior to HWA causing extensive damage and tree losses with areas found with HWA appeared to be recently infested.

Another aspect of the current situation that will work to our advantage is the distribution of hemlock stands on the Wayne. Hemlock occurs in small pockets that are surrounded by extensive mixed hardwood and occasional pine stands. This scattered distribution may make it hard for HWA to find nearby stands to spread into, as small, spread out patches of hemlock will be hard to

find, especially with the somewhat random spreading vector of attaching to birds, humans and other animals.

Management Considerations

There are several management alternatives when considering an HWA management program including chemical, biological control, and silvicultural treatment options. In addition, integrated pest management systems have been suggested that should also be considered. Most management programs use a combination of individual tree chemical treatments and biocontrol releases. Systemic insecticide treatments currently used are effective, long lasting, and have limited non-target effects. They are, however, labor intensive, making treatment of large areas of forests impractical. Despite this, many states and landowners are treating thousands of trees with pesticides with the hope that by the time retreatment of these trees is needed biological controls will have become effective at controlling outbreak populations, reducing the need for additional chemical treatments.

Foliar chemical treatments

There are foliar chemical treatments that could be effective treatments but are not used mainly due to the potential for extensive non-target effects. For example, aerial spraying with more toxic insecticides (e.g. malathion or diazinon) would have very significant impacts on a wide range of non-target insects and other animals and limited control benefits (Evans 2000). Horticultural oil sprays may be effective for smaller, landscape trees but are not an option because aerial sprays would not provide the needed "saturation" necessary to ensure that the insecticide adequately covers the insect. Also, application of insecticides using ground spraying equipment is generally limited to areas accessible to hydraulic spray equipment and areas where over spray or run off would not contaminate streams, lakes or ponds making this option undesirable. Backpack sprayers could be effectively used in limited situations for foliar treatment of infested seedlings and saplings to protect regeneration.

Systemic Insecticides

Several chemical insecticides are labeled for the control of hemlock woolly adelgid in forests and have been shown to be effective treatments (Webb et al. 2003; Ward et al. 2004). Use of systemic insecticides that can be applied with trunk injections, soil drench, soil injection or through bark basal sprays are the preferred chemical treatments due to limited movement of insecticide outside of treated trees (no drift associated with foliar spraying) and subsequent low non-target impacts. Neonicotinoids represent the most effective insecticide for controlling piercing sucking insects such as aphids, leafhoppers, planthoppers, thrips, fleas and some coleopteran, lepidopteran, and dipteran pests (Mullins 1993, Tomizawa and Casida 2005, Elbert et al. 2008). Factors that contribute to the success of this class of insecticides is their plant systemicity (Elbert et al. 2008), and mode of action, which offers no cross-resistance to other conventional long-established insecticides (Jeschke and Nauen 2008).

Two neonicotinoid pesticides, imidacloprid and dinotefuran, have become the choice of many land managers for treating HWA. Imidacloprid is commonly applied as a soil drench or injected into the soil around hemlock trees. Near-trunk soil placement of imidacloprid results in long-term moderate concentrations of imidacloprid in sap, which may be responsible for reliable, highly effective suppression of HWA (Cowles et al. 2005) and can be effective for HWA population

suppression for up to seven years (Benton et al. 2016). To avoid movement of imidacloprid into nearby streams or leaching into the soil profile and groundwater applications should avoid injecting into sandy or saturated soils.

Imidacloprid, with a mode of action similar to that of nicotine, functions as a fast-acting insect neurotoxicant (Schroeder and Flattum 1984) that binds to the post-synaptic nicotinic acetylcholine receptors (nAChRs) of the insects' central nervous system (Jeschke and Nauen 2008). Imidacloprid mimics the action of acetylcholine, the major excitatory neurotransmitter of insect's central nervous system (Lansdell and Millar 2000, Tomizawa and Casida 2003) and thereby heightens, then blocks the firing of the postsynaptic receptors with increasing doses (Schroeder and Flattum 1984, Felsot 2001). Acetylcholine is normally degraded by the inactivating enzyme acetylcholine esterase (Breer and Sattelle 1987) but because imidacloprid is not removed by acetylcholine esterase, it causes substantial disorder within the nervous system leading to tremors, paralysis and in most cases death (Mullins 1993, Smith and Krischik 1999). Dinotefuran also has the same mode of action, acting by binding to specific sub-sites of the nicotinic acetylcholine receptor (nAChR), which in turn activates nAChR activity (Tomizawa and Casida 2005) and leads to the same nervous system impacts.

Dinotefuran is applied to hemlock as a systemic insecticide through soil drench, soil injection, or basal bark spray. It is effective at protecting individual trees from HWA and is often used in situations where quick chemical uptake and rapid HWA mortality is needed. When HWA populations are already high and impacting the tree, for example. This is the main difference between these two systemics; imidacloprid takes longer to move throughout the tree and lasts up to seven years while dinotefuran is taken up more rapidly and is effective for two years (Cowles and Lagalante 2009). Dinotefuran is highly water soluble, which helps it move much more quickly into the foliage. In studies of rate of chemical uptake, researchers have shown that dinotefuran can begin to control HWA two weeks after treatment compared to imidacloprid which may take several months before becoming effective (Cowles et al. 2006; Cowles and Lagalante 2009).

Because it does not bind nerve receptors in mammals sufficiently to trigger nervous activity (Felsot 2001), imidacloprid is considered to have low to moderate mammalian toxicity (Mullins 1993). Chronic (repeated dose) toxicity studies have shown that imidacloprid is not carcinogenic nor mutagenic and demonstrates no primary reproductive toxicity (Mullins 1993). In addition to affecting piercing-sucking insects, activity has also been demonstrated for ants (Hymenoptera), termites (Isoptera), and cockroaches, grasshoppers, and crickets (Orthoptera). No activity has been demonstrated against nematodes nor spider mites (Mullins 1993).

Movement in soil and water and biological fate of chemical.....

Biological control

There are native natural enemies, such as predaceous gall midges (Diptera: Cecidomyiidae), lacewings (Neuroptera: Chrysopidae and Hemerobiidae), lady beetles (Coleoptera: Coccinellidae), and flower flies (Diptera: Syrphidae), that prey on HWA in low densities in eastern North America (McClure 1987, Montgomery and Lyon 1996, Wallace and Hain 2000). These predators are generalist (feed on a wide range of insects), however, and are not sufficient for controlling HWA infestations. Because of the lack of natural predators, researchers have worked to find non-native natural enemies of HWA for use as biocontrol agent that could reduce

HWA populations. So far, eight species of non-native predatory insects have been released in eastern North America; two imported from Japan, four from the Pacific Northwest in North America, and two from China (Onken and Reardon 2011).

Sasajiscymnus tsuga (Coleoptera: Coccinellidae) was the first biocontrol for HWA and brought from Japan in 1994 and 1995. This tiny beetle is an effective predator of HWA in Japan (McClure 1995, Sasaji and McClure 1997) and thought to be a good candidate for mass rearing (Cheah and McClure 2000). It was first released in Connecticut and then released in 16 additional eastern states (Cheah 2011). It established in Tennessee and Georgia and was found to coexist with other non-native and native predators of HWA (Hakeem et al. 2011, Jones et al. 2014) but has failed to survive across the full range where it was released and there is no concrete evidence that it is providing control (Limbu et al. 2018).



Figure 13. Beetles released for biocontrol (left to right): *Sasajiscymnus tsugae* from Japan, *Scymnus sinuanodus* from China and *Laricobius nigrinus* from Pacific Northwest.

Two predatory beetles from China, *Scymnus sinuanodus* and *Scymnus ningshanesis*, were studied as potential biocontrols for HWA. Releases were conducted in 2004 and 2007 but they were not found to establish (Montgomery and Keena 2011, Keena et al. 2012).

Two Derodontid beetles, *Laricobius nigrinus*, from the Pacific Northwest of North America (Zilahi-Balogh et al. 2006) and *Laricobius osakensis*, native to Japan (Montgomery et al. 2011) are also approved for release. *Laricobius nigrinus*, released

since 2003, has been collected from coastal areas of Oregon and Washington, as well as from inland sites in Idaho, Montana, and British Columbia. The inland population has exhibited more cold tolerance than coastal populations and have been released in the northern portions of the eastern HWA geographic range. The *L. nigrinus* biocontrol releases have been the most successful to date and have been able to establish in most sites in which they have been released. Individuals for release are now lab reared and field collected in both the Pacific Northwest and at field insectaries in the eastern United States in areas where population have been established.

Recent releases have mostly been of *L. nigrinus* and *L. osakensis*. Preferred release sites are newly infested sites where trees and adelgids are still healthy, but older infested sites where adelgid densities are low and recovery of hemlock trees is evident has also proven acceptable. Predator beetles are mostly laboratory reared and the number of predators available in any given year is variable depending in part, on the success of the rearing facilities to locate good quality host material for a food source. Field insectaries have also been established from which predator beetles can be collected and released in new areas.

Integrated Pest Management

Researchers have recently suggested the use of integrated pest management systems that combine both chemical and biocontrol treatments in the same area for increased long-term HWA suppression efficacy (e.g., Sumter et al. 2018, Mayfield et al. 2020). Although chemical treatments can protect a subset of trees until a time when other treatments are found to be more

effective and current biological control agents (*L. nigrinus* and *L. osakensis*) can reduce winter generation HWA populations, neither treatment alone has been found to be sufficient for long-term suppression and management of HWA populations.

Until recently most chemical and biocontrol treatments were separated to prevent chemical treatments from impacting biocontrol releases. Mayfield et al. (2020), however, have suggested that if properly timed chemical and biological control treatments may be implemented in the same stands. The goal is to prolong and improve hemlock health on certain hemlock trees through temporary insecticide protection, while simultaneously establishing predators on nearby untreated trees (Joseph et al. 2011b, Eisenback et al. 2014, Mayfield et al. 2015, Sumpster et al. 2018).

Ideally, when the chemical treatments loss their efficacy the established biocontrol can prevent HWA populations from rising to levels high enough to negatively impact the trees. Presently, available biocontrols will not be able to provide this type of effectiveness but current trails with additional biocontrol agents, namely Leucopis silver flies, have encouraged researchers that a biocontrol that could impact HWA during the summer months could be developed.

RECOMMENDATIONS

The Wayne National Forest should start an HWA management program that includes a combination of systemic insecticide treatments, biocontrol releases, and monitoring. Early indications are that HWA is present in a small percentage of hemlock stands and that tree damage is minimal at this time. In stands where HWA has been found, however, insecticide treatments should start as soon as is practical. Systemic insecticide treatments using imidacloprid are recommended for HWA control on accessible, high-value, infested hemlock trees in the New Matamoras site on the Marietta RD, and in the Lake Vesuvius site on the Ironton RD. Biocontrol agents, mainly *Laricobius nigrinus* and/or *L. osakensis* should also be released in stands with the appropriate conditions.

In most stands, it will not be possible to treat all the hemlock with insecticide treatments due to treatment rate limitations prescribed on produce label, as well as limits on personnel and available funding for this work. Treatment choice will be dependent on tree size, location, and infestation level. Most land managers choose to treat mature trees in dominant and co-dominant crown position. Trees greater than ten feet from water that have low levels of HWA-caused crown damage are best treated using soil drench or soil injection with an imidacloprid based product. This systemic pesticide treatment both limits non-target impacts and is the most effective treatment in both terms of chemical uptake and distribution within the tree, as well length of effectiveness (up to six years). Imidacloprid applied at 0.75 grams of a.i. per inch of trunk diameter (dbh) is recommended for the soil injections and should be done in the spring or fall when tree uptake is the best. For more information on determining the optimal dose of imidacloprid per tree for soil injections see the University of Georgia paper by Benton and Cowles (2016).

When treating trees close to water, stem injections should be used to avoid movement of pesticide into bodies of water. Also, in circumstances where rocky, porous soils exist or the organic layer is not sufficiently deep enough to handle the injector tip placement, trees should be treated using a stem injection system.

Dinotefuran may be used on trees where faster uptake is desired. Dinotefuran, although not remaining effective for as long as ivermectin, is taken up by the tree more rapidly by the tree and may be a good choice when high HWA on an individual tree need to be quickly knocked back.

Predatory beetle releases should take place in the spring or fall of the year when HWA are actively feeding. The establishment of biocontrol agents offers the opportunity for long-term control and may minimize the need for repeated chemical treatments in future years. Currently, Laricobius beetles have been successfully established in many areas and have shown the ability to impact the winter generation. A newer biocontrol, silver flies, that feeds during the summer is being released experimentally and offers some hope that, together with current biocontrols, HWA may be more effectively controlled by biocontrol agents in the absence of chemical treatments.

You may also choose to use an integrated pest management approach that has recently been suggested (see Mayfield et al. 2020). In this system, both chemical and biocontrol are used in the same stands. Staggering the treatments—waiting a year after chemical controls are applied in a stand to release biocontrols—can help to avoid biocontrols being poisoned by feeding on HWA that are feeding on pesticide treated trees. In this system the aim is to have biocontrols already established in a stand when the efficacy of the pesticides is waning.

As HWA was not found in all the stands visited and there are a limited number of hemlock stands on the Wayne NF, a monitoring system should be established to identify newly infested stands. Uninfected stands can be inspected using the same methodology used in this report. Because your stands are spread out and HWA spread is generally slow, you may be able to check stands on a rotation, visiting each stand every two or three years. This schedule can be adjusted as needed.

With the application of pesticide treatments on individual trees, the establishments of biocontrol agents, and a good monitoring system, the WNF should be able to limit hemlock losses due to HWA. The long-term goal is to limit losses until biocontrols can effectively control HWA populations. As the WNF has limited hemlock resources, if additional pesticide applications are needed it will be a feasible treatment to preserve these hemlock trees.

REFERENCES

- Barden, L.S. 1979. Tree replacement in small canopy gaps of a *Tsuga canadensis* forest in the southern Appalachians, Tennessee. *Oecologia* 44: 141-142.
- Benton, E.P., J.F. Grant, R.J. Webster, R.S. Cowles, A.F. Lagalante, A.M. Saxton, R.J. Nichols, and C.I. Coots. 2016. Hemlock woolly adelgid (Hemiptera: adelgidae) abundance and hemlock canopy health numerous years after imidacloprid basal drench treatments: implications for management programs. *J. Econ. Entomol.* 109: 2125-2136.
- Brantley, S.T., C.R. Ford, and J.M. Vose. 2013. Future species composition will affect forest water use after loss of eastern hemlock from southern Appalachian forests. *Ecol. Appl.* 23: 777-790
- Brantley, S.T., A.E. Mayfield, R.M. Jetton, C.F. Miniat, D.R. Zietlow, C.L. Brown, and J.R. Rhea. 2017. Elevated light levels reduce hemlock woolly adelgid infestation and improve carbon balance of infested eastern hemlock seedlings. *Forest Ecol. and Manag.* 385:150-160.
- Breer, H., and D.B. Sattelle. 1987. Molecular properties and functions of insect acetylcholine receptors. *J. Insect Physiol.* 33: 771-790.
- Butin, E., A.H. Porter, and J. Elkinton. 2005. Adaptation during biological invasions and the case of *Adelges tsugae*. *Evol. Ecol. Res.* 7: 887-900.
- Cheah, C.C. 2011. *Sasajiscymmus* (=*Pseudoscymmus*) *tsuga*, a ladybeetle from Japan, Chapter 4, pp 42-53. In B. Onken and R.C. Reardon (eds.), implementation and status of biological control of the hemlock woolly adelgid. USDA Forest Service, Forest Health Technology Enterprise Team, Publication FHTET_2011-04, Morgantown, WV.
- Cheah, C.A.S.J., 2017. Predicting hemlock woolly adelgid winter mortality in Connecticut forests by climate divisions. *Northeast. Nat.* 24: B90-B118.
- Cheah, C. A. S.-J. and M.S. McClure. 2000. Seasonal synchrony of life cycles between the exotic predator, *Pseudoscymnus tsugae* (Coleoptera: Coccinellidae) and its prey, the hemlock woolly adelgid *Adelges tsugae* (Homoptera: Adelgidae). *Agric. and For. Entom.* 2:241-251.
- Cheah, C.A.J., M.E. Montgomery, S. Salom, B.L. Parker, S. Costa, and M. Skinner. 2004. Biological control of hemlock woolly. U.S. Department of Agriculture, Forest Service, Forest Health Technology Enterprise Team, Morgantown, WV.
- Costa, S. and B. Onken. 2006. Standardized Sampling for Detection and Monitoring of Hemlock Woolly Adelgid in Eastern Hemlock Forests. FHTET-2006-16. U.S. Department of Agriculture, Forest Service, Forest Health Technology Enterprise Team; 11p.
- Cowles, R.S., and A.F. Lagalante. 2009. Activity and persistence of systemic insecticides for managing hemlock woolly adelgid, pp. 17-18, In K.A. McManus and K.W. Gottschalk (eds.), Proceedings, 20th U.S. Department of Agriculture interagency research forum on invasive species, Annapolis, MD. Gen. Tech. Rep. NRS-P-51, USDA Forest Service, Northern Research Station, Newtown Square, PA.

- Cowles, R.S., C.S.-J. Cheah, M.E. Montgomery. 2005. Comparing systemic imidacloprid application methods for controlling hemlock woolly adelgid. In Proceedings, 16th U.S. Department of Agriculture interagency research forum on gypsy moth and other invasive species. GTR-NE-337.
- Cowles, R.S., M.E. Montgomery, and C.A. Cheah. 2006. Activity and residues of imidacloprid applied to soil and tree trunks to control hemlock woolly adelgid (Hemiptera: Adelgidae) in forests. *J. Econ. Entomol.* 99: 1258-1267.
- Eisenback, B.M., S.M. Salom, J.T. Kok, and A.F. Lagalante. 2014. Impacts of truck and soil injections of low rates of imidacloprid on hemlock woolly adelgid (Hemiptera: Adelgidae) and eastern hemlock (Pinales: Pinaceae) health. *J. Econ. Entomol.* 107: 250-258.
- Elbert, A., M. Haas, B. Springer, W. Thielert, R. Nauen. 2008. Applied aspects of neonicotinoid uses in crop protection. *Pest Manag. Sci.* 64(11): 1099-1105.
- Elkinton, J.S., J.A. Lombardo, A.D. Roehrig, T.J. McAvoy, A. Mayfield, and M. Whitmore. 2017. Introduction of cold hardiness in an invasive herbivore: the case of the hemlock woolly adelgid (Hemiptera: Adelgidae). *Environ. Entomol.* 46: 118-124.
- Ellison, A.M., A.A. Barker-Plotkin, D.R. Foster, and D.A. Orwig. 2010. Experimentally testing the role of foundation species in forests: the Harvard Forest hemlock removal experiment. *Methods Ecol. Evol.* 1: 168-179.
- Evans, R.A. 2000. Draft Environmental Assessment: for the Release and Establishment of *Pseudoscymnus tsugae* (Coleoptera: Coccinellidae) as a Biological Control Agent for Hemlock Woolly Adelgid (*Adelges tsugae*) at the Delaware Water Gap National Recreation Area. USDI, National Park Service, Northeastern Region. 23 p.
- Evans, A.M., and T.G. Gregoire. 2007. A geographically variable model of hemlock woolly adelgid spread. *Biol. Invasions* 9: 369-382.
- Felsot, A. 2001. Admiring Risk Reduction: Does Imidacloprid have what it takes? *Agrichemical and Environmental News* 186: 2-13.
- Godman, R.M. and K. Lancaster. 1990. *Tsuga canadensis* (L.) Carr., eastern hemlock. In: R.M. Burns and B.H. Honkala, eds. *Silvics of North America*, vol.1, conifers. USDA Forest Service, Agriculture Handbook No. 654. pp. 604-612.
- Hakeem, A., J.F. Grant, G.J. Wiggins, P.L. Lambdin, and J.R. Rhea. 2011. Establishment and coexistence of two predators, *Laricobius nigrinus*, and *Sasajiscymnus tsugae*, introduced against hemlock woolly adelgid on eastern hemlock. *Biocontrol Sci. Tech.* 21: 687-691.
- Havill, N.P., and R.G. Foottit. 2007. Biology and evolution of adelgidae. *Annu. Rev. Entomol.* 52: 325-349.
- Havill, N.P., S. Shiyake, A. Lamb Galloway, R.G. Foottit, G. Yu, A. Paradis, J. Elkinton, M.E. Montgomery, M. Sano, and A. Caccone. 2016. Ancient and modern colonization of North America by hemlock woolly adelgid, *Adelges tsugae* (Hemiptera: Adelgidae), an invasive insect from East Asia. *Mol. Ecol.* 25: 2065-2080.

- Jeschke, P., and R. Nauen. 2008. Neonicotinoids—from zero to hero in insecticide chemistry. *Pest Manag. Sci.* 64(11): 1084-1098.
- Jones, C.E., N.P. Havill, J.L. Hanula, and S.K. Braman. 2014. Post release recovery of hemlock woolly adelgid predators in the north Georgia mountains. *J. Entomol. Sci.* 49: 383-400.
- Joseph, S.V., A.E. Mayfield, M.J. Dalusky, C. Asaros, and C.W. Berisford. 2011. Phenology of the hemlock woolly adelgid (Hemiptera: Adelgidae) in north Georgia. *J. Entomol. Sci* 46: 315-324.
- Keena, M.A., R.T. Trotter, C. Cheah, and M.E. Montgomery. 2012. Effects of temperature and photoperiod on the aestivo-hibernal egg diapause of *Scymnus camptodromus* (Coleoptera: Coccinellidae). *Environ. Entomol.* 41: 1662-1671.
- Kinahan, I.G., G. Grandstaff, A. Russell, C.M. Rigsby, R.A. Casagrande, E.L. Preisser. 2020. A four-year, seven-state reforestation trial with eastern hemlocks (*Tsuga canadensis*) resistant to hemlock woolly adelgid (*Adelges tsugae*). *Forests* 11, 312.
- Lansdell, S.J., and N.S. Millar. 2000. The influence of nicotinic receptor subunit composition upon agonist, α -bungarotoxin and insecticide (imidacloprid) binding affinity. *Neuropharmacology* 39: 671-679.
- Lapin, B. 1994. The Impact of Hemlock Woolly Adelgid on Resource in the Lower Connecticut Valley. USDA. Northeastern Center for Forest Health research, Hamden, CT. 45p.
- Limbu, S., M.A. Keena, M.C. Whitmore. 2018. Hemlock woolly adelgid (Hemiptera: Adelgidae): a non-native pest of hemlocks in eastern North America. *J of Integrated Pest Management* 9(1): 27, <https://doi.org/10.1093/jipm/pmy018>
- Lombardo, J.A., and J.S. Elkinton. 2017. Environmental adaptation in an asexual invasive insect. *Ecol. Evol.* 7: 5123-5130.
- Mayfield, A.E., B.E. Reynolds, C.I. Coots, N.P. Havill, C. Brownie, A.R. Tait, J.L. Hanula, S.V. Joseph, and A.B. Galloway. 2015. Establishment, hybridization and impact of *Laricobius* predators on insecticide-treated hemlocks: exploring integrated management of the hemlock woolly adelgid. *For. Ecol. Manage.* 335: 1-10.
- Mayfield, A.E., III; S.M. Salom; K. Sumpter; T. McAvoy; N.F. Schneeberger; R. Rhea. 2020. Integrating chemical and biological control of the hemlock woolly adelgid: a resource manager's guide. FHAAST-2018-04. USDA Forest Service, Forest Health Assessment and Applied Sciences Team, Morgantown, West Virginia.
- McClure, M.S. 1987. Biology and control of hemlock woolly adelgid. Connecticut Agricultural Experiment Station, New Haven, CT, Bulletin 851, 9pp.
- McClure, M.S. 1989. Evidence of a polymorphic life cycle in the hemlock woolly adelgid, *Adelges tsugae* (Homoptera: Adelgidae). *Ann. Entom. Soc. Am.* 82:50-54.
- McClure, M.S. 1990. Role of wind, birds, deer, and humans in the dispersal of hemlock woolly adelgid (Homoptera: Adelgidae). *Environ. Entomol.* 19: 36-43.

- McClure, M.S. 1995. Managing hemlock woolly adelgid in ornamental landscapes. Bulletin 925. Connecticut Agricultural Experiment Station. 7 p.
- McClure, M.S. 1996. Biology of *Adelges tsugae* and its potential for spread in the Northeastern United States. In: Salom, S.M., T.C. Tigner, and R.C. Reardon, (Eds.), Proceedings, First hemlock woolly adelgid review, 12 October, 1995, Charlottesville, VA. USDA, Forest Service, Forest Health Technology Enterprise Team, Morgantown, WV, FHTET-96-10: 16-25.
- McClure, M.S., S.M. Salom, and K.S. Shields. 2001. Hemlock woolly adelgid. USDA, Forest Service, Forest Health Technology Enterprise Team, Morgantown, WV, FHTET-2001-03. 14 p.
- Mech, A.M., P.C. Tobin, R.O. Teskey, J.R. Rhea, and K.J.K. Gandy. 2017. Increases in summer temperatures decrease the survival of a invasive forest insect. *Biol. Invasions* 20: 365-374.
- Montgomery, M.E. and S.M. Lyons. 1996. Natural enemies of adelgids in North America: Their prospect for biological control of *Adelges tsugae* (Homoptera: Adelgidae). In: Salom, S.M., T.C. Tigner, and R.C. Reardon, (Eds.), Proceedings, First hemlock woolly adelgid review, 12 October, 1995, Charlottesville, VA. USDA, Forest Service, Forest Health Technology Enterprise Team, Morgantown, WV, FHTET-96-10: 89-102.
- Montgomery, M.E., and M.A. Keena. 2011. Chapter 5: *Scymnus* (*Neopullus*) lady beetles from China, pp. 89-102. In B. Onken and R.C. Reardon (eds.) Implementation and status of biocontrol of the hemlock woolly adelgid. USDA Forest Service, Forest Health Technology Enterprise Team, Publication FHTET-2011-04, Morgantown, WV.
- Montgomery, M.E., S. Shiyake, N.P. Havill, and R.A.B. Leschen. 2011. A new species of *Laricobius* (Coleoptera: Derodontidae) from Japan with phylogeny and a key for native and introduced congeners in North America. *Ann. Ent. Soc. Am.* 104: 389-401.
- Mullins, J.W. 1993. Imidacloprid: a new nitroguanidine insecticide. In: Duke, S.O., J.J. Menn, and J.R. Plimmer (eds.), Pest control with enhanced environmental safety. American Chemical Society Symposium, ASC, Washington DC: 183-189.
- Onken, B., and R. Reardon (eds.). 2011. Implementation and status of biological control of the hemlock woolly adelgid. U.S. Department of Agriculture, Forest Service, Pub. FHTET-2011-04, Morgantown WV.
- Onken, B., D. Souto, and R. Rhea. 1999. Environmental Assessment for the release and establishment of *Pseudosymnus tsugae* (Coleoptera: Coccinellidae) as a biological control agent for the hemlock woolly adelgid. USDA, Forest Service, Morgantown, WV.
- Paradis, A., J. Elkinton, K. Hayhoe, and J. Buonaccorsi. 2008. Role of winter temperature and climate change on the survival and future range expansion of the hemlock woolly adelgid (*Adelges tsugae*) in eastern North America. *Mitig. Adapt. Strat.* 13: 541-554.
- Parker, B.L., M. Skinner, S. Gouli, T. Ashikaga, and H.B. Teillon. 1998. Survival of hemlock woolly adelgid (Homoptera: Adelgidae) at low temperatures. *Forest Sci.* 44: 414-420.

- Parker, B.L., M. Skinner, S. Gouli, T. Ashikaga, and H.B. Teillon. 1999. Low lethal temperature for hemlock woolly adelgid (Homoptera: Adelgidae). *Environ. Entomol.* 28: 1085-1091.
- Quimby, J. 1996. Value and importance of hemlock ecosystems in the eastern United States. In: S>M> Salom, T.C. Tigner, and R.C. Reardon, eds. *Proceedings of the First Hemlock Woolly Adelgid Review*, Charlottesville, VA, 1995. USDA Forest Service, Forest Health Technology Enterprise Team-Morgantown, WV. FHTET 96-10. pp1-8.
- Ross, R.M., L.A. Redell, and R. Bennett. 2004. Mesohabitat Use of Threatened Hemlock Forests by Breeding Birds of the Delaware River Basin in Northeastern United States. *Natural Areas Journal*, 24:307-315.
- Sasaji, H. and M.S. McClure. 1997. Description and distribution of *Pseudoscymnus tsugae* sp. Nov. (Coleoptera: Coccinellidae), an important predator of hemlock woolly adelgid in Japan. *Annals of the Ent. Soc. Am.*, 90:563-578.
- Schroeder, M.E. and R.F. Flattum. 1984. The mode of action and neurotoxic properties of the nitromethylene heterocycle insecticides. *Pestic. Biochem. Physiol.* 22: 148-160.
- Skinner, M., B.L. Parker, S. Gouli, and T. Ashikaga. 2003. Regional responses of hemlock woolly adelgid (Homoptera: Adelgidae) to low temperatures. *Environ. Entomol.* 32: 523-528.
- Smith, S.F. and V.A. Krischik. 1999. Effects of systemic imidacloprid on *Coleomegilla maculata* (Coleoptera: Coccinellidae). *Envir. Entomol.* 28(6): 1189-1195.
- Snyder, C., J. Young, D. Smith, D. Lemarie, R. Ross, and R. Bennett. 1998. Influences of eastern hemlock decline on aquatic biodiversity of Delaware Water Gap National Recreation Area. Final Report to the National Park Service.
- Sumter, K.L., T.J. McAvoy, C.C. Brewster, A.E. Mayfield, S.M. Salom. 2018. Assessing an integrated biological and chemical control strategy for managing hemlock woolly adelgid in southern Appalachian forests. *For. Ecol. Manage.* 411: 12-19.
- Tomizawa, M., and J.E. Casida. 2005. Neonicotinoid insecticide toxicology: mechanisms of selective action. *Annual Review of Pharmacology and Toxicology* 45:1, 247-268
- Trotter, R.T., and K.S. Shields. 2009. Variations of winter survival of the invasive hemlock woolly adelgid (Hemiptera: Adelgidae) across the eastern United States. *Environ. Entomol.* 38: 577-587.
- Sussky, E.M, and J.S. Elkington. 2015. Survival and near extinction of hemlock woolly adelgid (Hemiptera: Adelgidae) during summer aestivation in a hemlock plantation. *Environ. Entomol.* 44: 153-159.
- Tomizawa, M., and J.E. Casida. 2005. Neonicotinoid insecticide toxicology: mechanisms of selective action. *Annual Review of Pharmacology and Toxicology*, 45: 247-268.
- USDA Forest Service. 2021. Distribution of HWA in 2020. <http://hiro.ento.vt.edu/hwa/wp-content/uploads/2021/03/hwa2020.pdf>

- Wallace, M.S. and F.P. Hain. 2000. Field surveys and evaluation of native and established predators of the hemlock woolly adelgid (Homoptera: Adelgidae) in the southeastern United States. *Environ. Entomol.* 29: 638-644.
- Ward, J.S., M.E. Montgomery, C.A.S.J. Cheah, B.P. Onken, and R.S. Comles. 2004. Eastern hemlock forests: guidelines to minimize the impacts of hemlock woolly adelgid. NA-TP-03-04, USDA Forest Service, Northeastern Area State and Private Forestry, Morgantown, WV.
- Webb, R.E., J.R. Frank, and M. J. Raupp. 2003. Eastern hemlock recovery from hemlock woolly adelgid damage following Imidacloprid therapy. *Journal of Arboriculture*. 29(5): 298-302.
- Weed, A.S., J.S. Elkington, and N.K. Lany. 2016. Destiny-dependent recruitment and diapause in the spring-feeding generation of hemlock woolly adelgid (Hemiptera: Adelgidae) in Western North America. *Environ. Entomol.* 45: 1352-1359.
- Yamasaki, M., R.M. DeGraaf, and J.W. Lanier. 2000. Wildlife habitat associations in eastern hemlock – birds, smaller mammals, and forest carnivores. In: Proceedings of a Symposium on Sustainable Management of Hemlock Ecosystems in Eastern North America, edited by K.A. McManus, K.S. Shields, and S.R. Souto. pp.135-141.
- Zilahi-Balogh, G.M.G., L.M. Humble, L.T. Kok, and S.M. Salom. 2006. Morphology of *Laricobius nigrinus* (Coleoptera: Derodontidae), a predator of the hemlock woolly adelgid. *Can. Entomol.* 138: 595-601.